A NOVEL CONCEPT

The LNG industry needs novel ideas to promote reduction in cost and schedule. In this context, Statoil and Linde have entered into a long term LNG Technology Alliance, aimed at more cost effective technology, project execution and operation of LNG baseload plants. As a prerequisite, novel LNG process concepts and careful machinery selection must be complemented by the capability of producing large heat exchangers for the cryogenic process section.

Accordingly, the alliance has developed a new LNG process (mixed fluid cascade or MFC® process) resulting in a plant concept, which allows significant reduction of plant investment cost and increased thermal efficiency. The baseload plant will be equipped with main cryogenic heat exchangers from Linde's own workshops. The design and manufacturing of these heat exchangers is based on reputable scientific methods and the experience of a large number of gas separation and liquefaction plants, where spiral wound as well as plate-fin heat exchangers have been tailor made for each specific application.

The MFC® process features three independent refrigeration cycles. Each of these cycles can be optimised with respect to energy consumption, operation and availability of critical equipment. The selection criteria for cycle compressors and drivers are presented for various situations. The benefits of liquid turbine expanders are discussed in this article. The number of expanders and the outlet condition (single phase/two phase) of the fluid offer room for savings.

The MFC® process with its three independent refrigeration cycles offers more possibilities than any other process with only two refrigerant cycles to accommodate high liquefaction capacities in one single train. Using only two Frame 7 gas turbines will be good for up to 6.3 million tpy LNG.

Mission

In 1995, Den Norske Stats Oljeselskap a.s. (Statoil) and Linde AG met to discuss the present situation of large LNG baseload plants. Eventually, the Statoil-Linde LNG Technology Alliance was formed with the objective to develop and market a novel concept with reduced costs and schedules.

Statoil, a major player in the oil and gas industry in Europe, and Linde AG, an engineering company with broad experience both in cryogenic processing and contracting of world scale projects formed an integrated team. It was clear from the beginning that they should both be independent of well established licensors of core technology or suppliers of proprietary equipment. Thus, a liquefaction process had to be identified, which was an improvement over existing solutions.

Process concept

Large baseload LNG plants typically consume at least 5% of the feed stock for internal purposes. Most of this 'shrinkage' is caused by the energy demand of the refrigerant compressors. Even if fuel gas were abundantly available at low cost, a highly efficient process design is mandated by

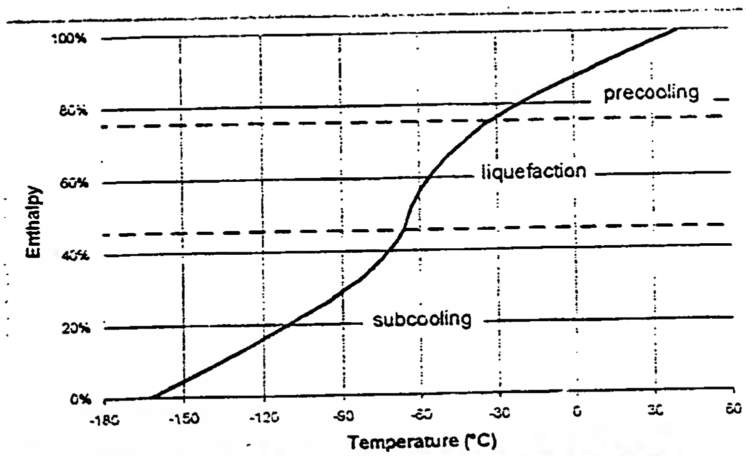
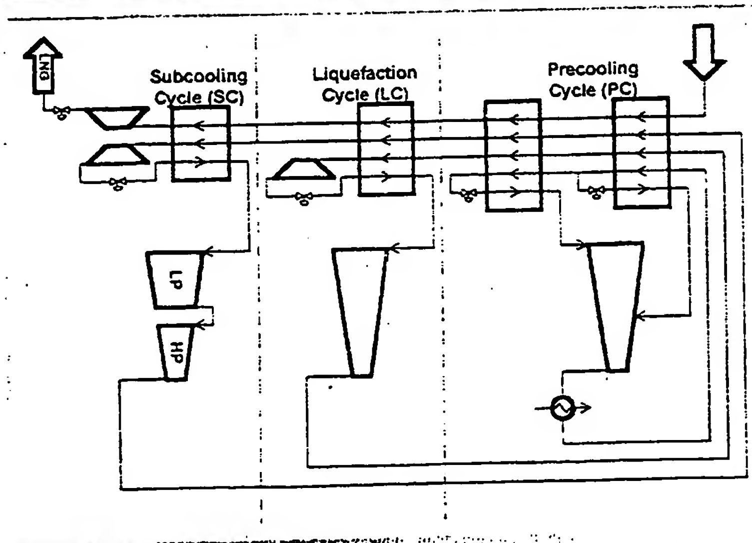


Figure 1. Typical cooling curve [illegible]



environmental considerations to minimise the emission of CO_2 and other pollutants.

Screening of the different refrigeration processes demonstrates the superiority of condensation based systems over those systems, which rely on gas compression and expansion only[1]. This is caused by the ability of condensation cycles to reject the bulk of the heat, which has been absorbed from the natural gas on its way to subcooled LNG, during the condensation of the refrigerant to the ambient. Expander processes without condensation eventually reject the absorbed heat as heat of compression, which is much more inefficient.

The bent cooling curve of natural gas under typical conditions (Figure 1) can be approached best either by a set of pure refrigerants vaporising at different pressure levels, by mixed refrigerants with a wide boiling range or by a combination of both.

Some of these combinations have reached a noticeable market share. Fair efficiencies are provided by cascaded systems using three pure refrigerants (e.g. Philips Optimized Cascade Process[2]) or by single flow mixed refrigerant cycles (e.g. PRICO™ Process[3]). Higher efficiencies can be achieved by designs with a dedicated precooling cycle upstream of a mixed refrigerant cycle used for liquefaction and subcooling. Propane precooling is used by APCI[4], another mixed refrigerant cycle for precooling is used e.g. by Shell[1].

The MFC® process

The Statoil/Linde process[5] was developed with the objective to push this state-of-the-art technology to new limits. After an extended period of process synthesis and optimisation three independent mixed refrigerant cycles with a reduced number of components each have been combined to a cascaded system (Figure 2).

Needless to say, this MFC® process has a leading edge energy consumption (~250 - 330 kWh/t_{LNG} depending on site conditions). Each cycle can be perfectly tuned to the actual task (precooling, liquefaction, subcooling) even under changing feed gas conditions caused, e.g. by depletion of the well or seasonal temperature changes.

The use of three cycles results in balanced and still moderate line sizes especially for the LP suction lines of the compressors. In addition, the train capacity can be increased in the future up to 7 - 8 million tpy LNG, as the design of the relevant (spiral wound)

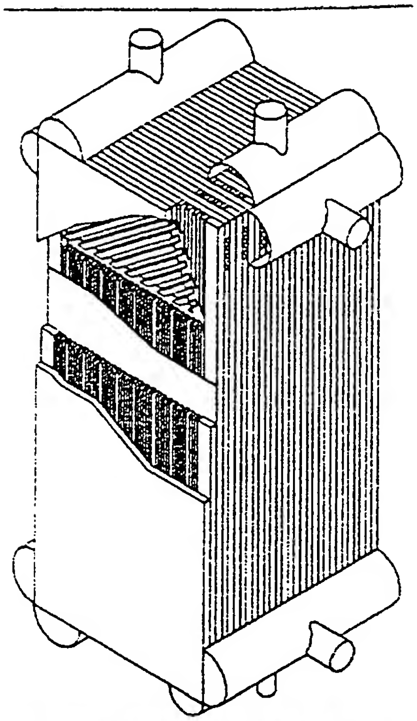


Figure 3. Brazed plate-fin heat exchanger.

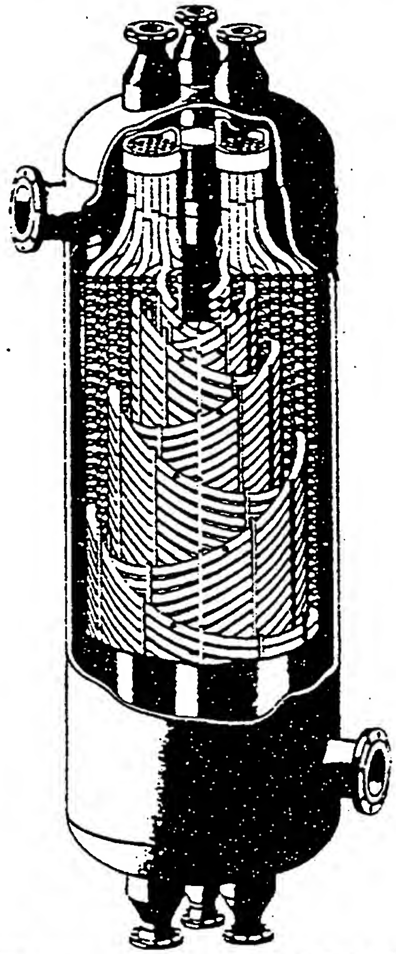


Figure 4. Spiral wound heat exchanger.

heat exchangers, predominantly for the liquefaction step is less complex and more compact.

Cryogenic heat exchangers

Reliable and cost effective cryogenic heat exchangers are required to make the promises of the process designer come true. Basically, two different types of heat exchangers are competing: brazed aluminium plate-fin heat exchangers (Figure 3) and spiral wound heat exchangers (Figure 4). The major differences between these two types are listed in Table 1.

Whereas brazed plate-fin heat exchangers are widely used in a broad range of cryogenic processes, design and manufacturing of spiral wound heat exchangers requires special know-how, which is not publicly available. With more than 100 years of experience in heat transfer by means of spiral wound heat exchangers[6], Linde compiled all the necessary information to build spiral wound cryogenic heat exchangers for LNG plants. Important issues are understanding the heat transfer of vaporising multi-component falling films, the even distribution of the fluid on the shell side, and the mechanical integrity of the equipment under thermal shocks. All relevant information has been developed based on rigorous methods, checked in laboratory experiments and corroborated in pilot plants.

Linde is in the fortunate situation to be designer and manufacturer of both types of heat exchangers. Thus, the selection of the best choice is governed by suitability only, not by availability. A detailed analysis of all applicable criteria recommended the use of brazed plate-fin heat exchangers for the precooling section and spiral wound heat exchangers in the liquefaction and subcooling section of the MFC® process.

Driver concepts

Large baseload LNG plants require a significant amount of energy to drive the refrigerant compressors. This energy can be provided by steam turbines, gas turbines (industrial or aeroderivative type) or electric motors. In the early phase of the LNG industry until approximately 1983 most of the LNG plants had been equipped with steam turbine drivers. Since then, most of the LNG plants had been designed with gas turbines. Electric motor drivers fed from a public grid are not used for large liquefaction capacities.

Most major LNG projects, which are under discussion today, are based

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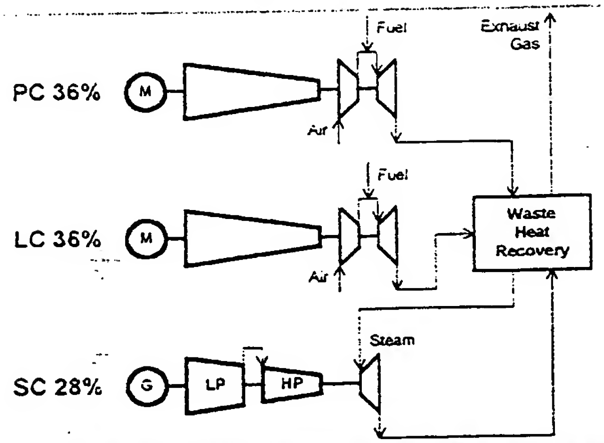
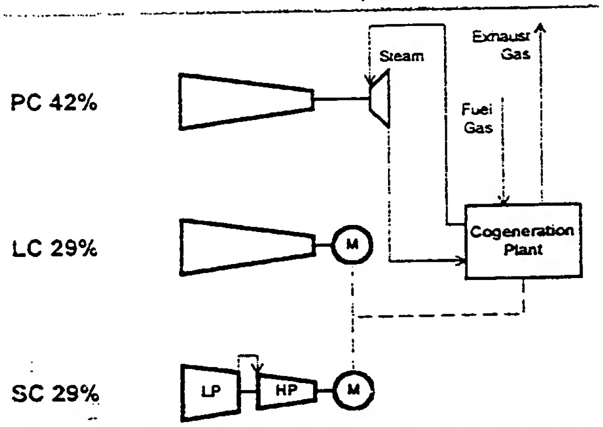
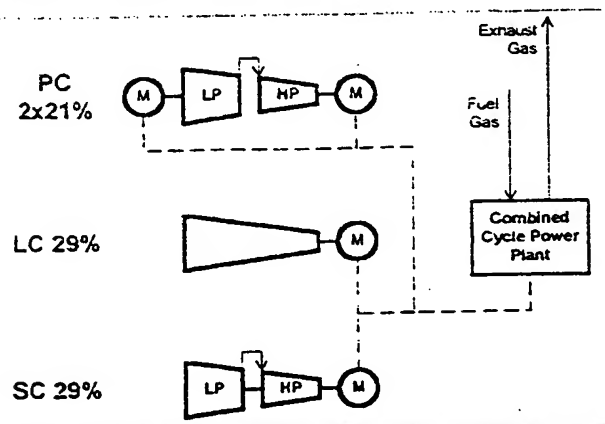
Table 1. Comparison of heat exchanger types

Brazed plate-fin heat exchanger	Spiral wound heat exchanger
Low cost per unit area	Large heating surface per unit
Complex stream arrangement possible	Tolerant against thermal shocks
Readily available from many qualified suppliers	Fixing of single tube leakages within moderate down time
Limited size per unit, parallel units with expensive manifolding for larger plant capacities	Proprietary equipment
Limited acceptable temperature gradients	Only one shell side stream possible







on a train capacity of at least 4 million tpy LNG. It is to be expected that this figure will grow further to 5 million tpy LNG and more for projects with an intended startup after 2010. Therefore, a hypothetical train capacity of 6 million tpy LNG has been considered for this comparison of driver concepts.

An average capacity of 6 million tpy LNG results in an average net liquefaction rate of 735 tph LNG, if 340 operating days per year are targeted. This is equivalent to an availability of 93%, which has been demonstrated in diligently designed plants.

Most of the known gas resources suitable for base load LNG production have been identified in areas with warm climate and limited fresh water resources. Accordingly, a specific energy consumption of 310 kWh/t_{LNG} will be used to get realistic figures. All together, 6 mtpy LNG liquefaction capacity requires 228 MW shaft power for the refrigeration compressors. This does not allow for the energy consumption of fuel gas compressors and other rotating equipment.

Gas turbines for mechanical drive

The largest gas turbine, which is widely accepted as mechanical drive for gas compressors is the General Electric MS7001EA (so called Frame 7) with an ISO rating of 81.59 MW in case natural gas is used as fuel. Two Frame 7 would supply approximately 163 MW or 72% of the required power.

The efficiency of a Frame 7 at ISO conditions is approximately 33%, which results in an exhaust temperature of well above 500 °C. Therefore, it will be the preferred solution to recover the missing 28% or 65 MW power from a waste heat recovery system instead of installing a third Frame 7.

The combination of two Frame 7 gas turbines and one steam turbine with the MFC® process is straight forward (Figure 5). One gas turbine shares the shaft with the (single casing) precooling cycle (PC) compressor and the required starter/helper motor, the other one shares the shaft with the (single casing) liquefaction cycle (LC) compressor and the required starter/helper motor. The subcooling cycle (SC) compressor is driven by the steam turbine. In case the waste heat recovery is more efficient than required to provide 28% of the overall shaft power, an electric generator will recover the surplus of energy.

Cogeneration of electricity and steam

The above solution may be considered as the best choice in case there is no infrastructure for adequate power supply available. If the LNG plant, however, is intended to be part of an integrated production site, a conversion of fuel gas outside of the plant battery limits to other forms of energy such as electricity or steam will be more cost effective.

In this case fuel gas, which may be tail gas from the LNG plant or gas from other sources, is used to generate electricity and steam in an industrial power plant. This plant may supply energy to several LNG plant trains or other nearby consumers. Economy of scale and optimised efficiency of this type of power plant will improve the overall profitability of the LNG plant.

In a jointly used cogeneration plant usually the ratio of steam to electricity is shifted towards more steam, as surplus electricity can be marketed more readily over longer distances.

If electric motors have to be used for an MFC® process with 6 million tpy LNG production, the maximum proven size of (preferably variable speed) drives has to be considered. Presently, units with up to 60 MW are proven technology. As this article discusses solutions for the future, a higher [illegible]

duty will be acceptable.

The proposed solution (Figure 6) requires two identical electric motors with 66 MW each driving the liquefaction cycle compressor and the subcooling cycle compressor. The precooling cycle compressor is powered by a steam turbine with 96 MW output.

All electric drives with combined cycle power generation

The ultimate step of disintegrating the LNG plant from the power generation is a concept, in which only electric energy is used to drive all refrigerant cycle compressors (Figure 7).

The required electric energy may be generated by whatever suitable technology. As natural gas supposedly is readily available, a combined cycle power plant is a very strong competitor for the most cost effective solution. Replacing the gas turbine driver for the large precooling cycle (PC) compressor discussed above with one single electric motor would exceed the proven size of this item. Therefore a split of the PC compressor into either 2 x 50% machines or an LP and a hp casing, driven by 48 MW motors each, will be required.

Use of liquid expanders

Most of the recent LNG projects make use of liquid expanders to increase the liquefaction capacity without need for more shaft power on the refrigerant compressors. The most suitable stream for liquid expansion is the subcooled LNG at the cold end of the chain of cryogenic heat exchangers. Liquid expansion of subcooled mixed refrigerant streams is discussed and decided case by case. As the MFC® process uses a concept for the refrigerant cycles, which is different from competing technologies, a critical examination of the cost effectiveness for refrigerant expanders is required.

Figure 1 shows all streams that are eligible for expansion in a liquid turbine: firstly, LNG before let down to storage pressure; secondly, the subcooling cycle refrigerant (SCR) and thirdly, the liquefaction cycle refrigerant (LCR). All three streams are significantly subcooled at the process conditions upstream of the expansion to low re-vaporisation pressure.

Single phase expanders

Most liquid expanders that are available today operate in the liquid phase of the process stream only. To ensure this the design outlet conditions should still be in the subcooled liquid phase. Thus, the usable pressure drop for a liquid phase expander is smaller compared to the available total pressure drop.

Figure 8 shows the results of process simulations, which are based on a constant energy consumption of all three refrigerant compressors and a driver concept (Figure 5). The left part of the twin columns refers to single phase expanders, the right part to two phase expanders using the full pressure drop. Energy savings are due to the power output from the generators, which are driven by the liquid expanders. Changes in the required heating surface are caused by the increased plant capacity.

In this case only one liquid expander shall be installed, obviously the LNG expander is the best choice. The LNG expander has the largest capacity gain of approximately 2.7%, which is equivalent to approximately 160 000 tpy LNG for a base capacity of 6 million tpy LNG. The addition of a second liquid expander is almost a tie between the SCR and the LCR expander. The marginal power generation of the SCR expander is compensated by the benefit of unchanged heat exchanger sizes.

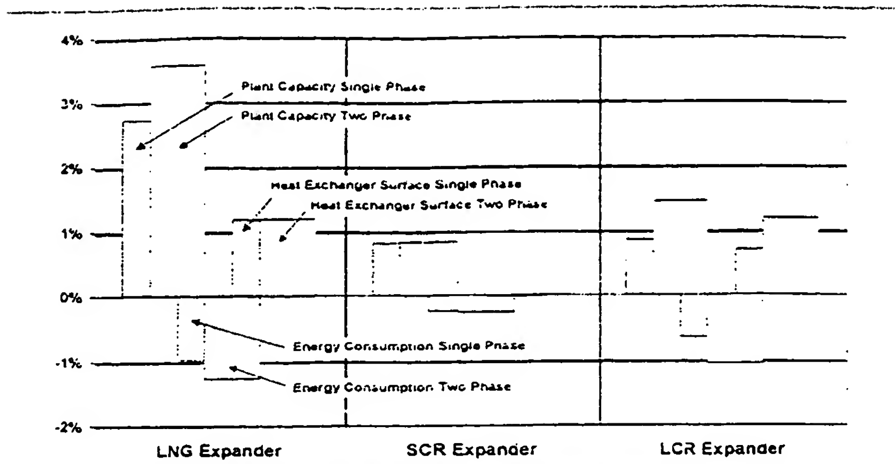


Figure 8. Liquid expanders in the MFC process

Two phase expanders

Liquid expander manufacturers are moving towards improved designs, which can tolerate a vapour fraction at outlet conditions of the turbine. Even if the acceptable vapour fraction is quite small today, it is good to know about the potential of a hypothetical expander, which uses the full pressure drop of the process stream.

The capacity increase of a two phase LNG expander compared to a single phase LNG expander will be similar to the additional installation of either a single phase SCR expander or a single phase LCR expander. In case two, two phase expanders will be installed, the preference for the LCR expander is now obvious as the SCR expander will hardly benefit from the larger pressure drop.

There is a long way to go for liquid expander manufacturers using the entire available pressure drop, as the vaporisation rate in the LNG and LCR expanders will be high. The two phase streams will have a vapour fraction of approximately 10 mol% each, which is equivalent under the actual process conditions to 90 - 95% vapour on a volumetric basis. The total capacity gain of two phase LNG plus LCR expanders will be 5% or 300 000 tpy LNG for a base capacity of 6 million tpy LNG.

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